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Quantitative assessment of the control capability of the trunk muscles during oscillatory bending motion under a new experimental protocol

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Abstract

Objective. A new quantitative technique for measuring the trunk control capability/coordination was to be developed in this study.
Design. Fitts' experimental paradigm was employed to quantify the information processing capacity (bits/s) of the trunk as well as dynamic motor performance such as velocity and acceleration during flexion and extension.
Background. The quantification of functional capability of the trunk such as range of motion, strength, and endurance have been used to evaluate low back pain patient. Especially, dynamic trunk motion during flexion and extension has been studied not only to quantify the severity of the low-back impairment but to classify patients.
Method. A lumbar motion monitor was used to record the time series of range of motion (RoM) and compute the velocity and acceleration of the trunk motion. Twenty male subjects without any back pain in the past 6 months and previous history of back injury participated. Each subject performed 22 controlled flexion/extension at predetermined RoMs as well as one ballistic trunk flexion/extension at a self-selected RoM.
Results. The information processing capacity of the trunk among healthy subjects was found to have a mean of 4.23 (SD 1.43) bits/s based on Fitts' law. Also, the velocity of dynamic trunk motion was measured with a considerable reduction in intersubject variability when the RoMs were controlled. A short but still accurate experimental protocol was suggested via a series of statistical analyses to provide an objective and easy-to-use method to evaluate the functional capacity of low-back pain patients.

Relevance

The information processing capacity may quantitatively represent the functional deficit of neuromuscular system of the trunk. Also, this protocol provides the trunk velocity information with a smaller within group variability under controlled RoM. This method is expected to increase the sensitivity and specificity in identifying the trunk performance of healthy subjects and LBP patients without exacerbating the injury or pain due to an excessive exertion. Copyright © 1996 Elsevier Science Ltd.

Key words: Trunk motion, control capability, Fitts' law, low-back pain, functional assessment

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Introduction

Epidemiology

Low back pain (LBP) has been one of the most common and costly musculoskeletal problems in the working place[1] and it is the most frequent and disabling condition affecting people in their productive ages[2]. Epidemiological studies[3–6] have shown that as many as 85% of adults have had back pain experience interfering with work or recreational activity. Economically this low-back problem costs $16 billion to over $50 billion dollars per year including medical costs and lost wages in the United States[7]. It was reported that 33% of total workers' compensation was spent by 16% of those having low back injuries[8].

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Functional assessment of low-back pain/disorder

In order to treat low-back patient properly, it is essential to have an accurate diagnosis. However, based on the current medical technology such as X-ray, magnetic resonance image (MRI), and computed tomography (CT) scan, only 12–15% of LBP patient indicate anatomical findings[6]. Therefore, the functional aspects of the trunk such as range of motion[9], strength[10], and endurance[11] have been introduced and proven as relatively reliable measures to evaluate LBP patient. Especially, dynamic trunk motion during flexion and extension has been studied to quantify the severity of the low-back pain. For instance, McIntyre et al.[12] measured a preferred dynamic trunk motion against resistance at 50% of subject's maximum voluntary contraction (MVC) and found the difference in average angle of flexion and average cycle velocity between normal and low-back patients group. Recently, Marras et al.[13,14] investigated the functional differences of normal and injured populations in terms of range of motion (RoM), velocity, and acceleration during free dynamic oscillatory bending motion, and successfully classified them into normal subjects and LBP patients (sensitivity, 94%, specificity, 88%). The functional assessment of dynamic trunk motion has been also recognized by clinicians. For instance, Mooney[15] emphasized the need of measuring dynamic trunk function to assess the normal capacity before injury. Nelson[16] used the aggravation of pain during repeated flexion and extension as a reliable sign of low back problem. McKenzie[17] also used repetitive flexion and extension to promote the centralization of pain as a part of his conservative treatment of LBP. Likewise, as more clinicians use the functional evaluation of the trunk motion, it becomes more important to have an accurate and easy-to-use method for quantitatively assessing the dynamic function of the trunk.

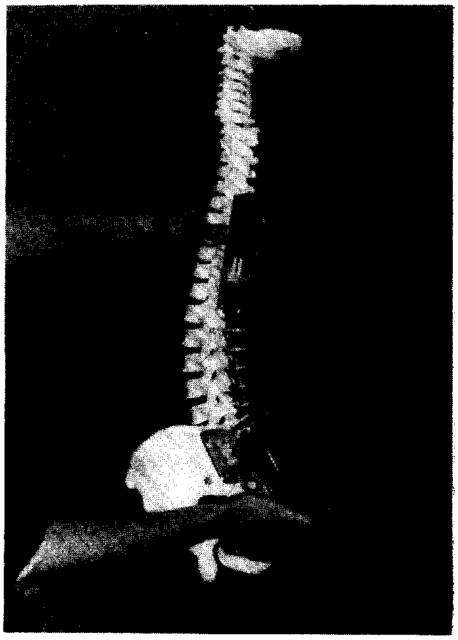

Figure 1. Lumbar Motion Monitor (LMM).

Variability during an oscillatory free dynamic trunk motion

During dynamic trunk flexion/extension motion it was observed that the velocity and acceleration were significant factors discriminating LBP patients from healthy subjects[13]. However, it was observed that the flexion velocity ($r = 0.89$, $P < 0.0001$) and extension velocity ($r = 0.93$, $P < 0.0001$) covaried with the self-selected RoM[13], which implies that the variation in the RoM can create an accompanying covariability in velocity or acceleration. This inherent variability from the self-selected RoM could affect the sensitivity or specificity in separating between the normal and patient group in terms of dynamic performance. Hence in this study it was hypothesized that the within-group variability of trunk velocity and acceleration could be reduced by controlling the RoM. This hypothesis was examined under Fitts' experimental protocol in which the RoMs were predetermined.

Controlled RoM under Fitts' experimental paradigm

Fitts' experimental protocol was originally designed to measure the information processing capacity of human arm movement during a tapping task between predetermined RoM and targets[18]. Fitts hypothesized that the movement would take more time if the ratio of movement amplitude (A: RoM) to target (W: width) was higher because more information processing was required. He described the information processing capacity in terms of the slope of regression line derived from movement time (MT) and index of difficulty (ID) (Equation 1). Subsequently this experimental framework has been applied to other joints of the body[19–21], and the basic linear relationship between MT and ID was observed in various experimental conditions. Fitts' law also described the speed–accuracy trade-off during motor control movement[22]. Thus, Fitts' experimental paradigm was used in this study to measure both control capability/coordination and dynamic motor performance such as flexion/extension velocity and acceleration with predetermined RoM. The Fitts' equation is described as follows:

$$\text{MT (movement time)} = a + b * ID \text{ (index of difficulty)} \qquad (1)$$

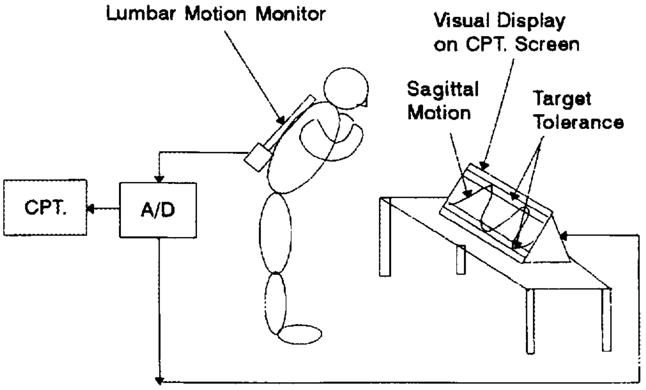

Figure 2. Data acquisition system.

where a is an intercept and b is a slope of this linear regression line; 1/b is considered as information processing capacity (bits/s). The index of difficulty is determined by range of motion (A: amplitude of movement) and target tolerance (W: width of target). That is, ID = $\log_2(2A/W)$. A more detailed description is provided in the Appendix.

Goals

The first goal of the study is to develop a protocol based on Fitts' law and use it for the first time to evaluate trunk motor performance. The second goal is to shorten or modify the protocol to accomodate the physical limitation of LBP patients without losing the accuracy of the original protocol.

Methods

Subjects

Twenty healthy male subjects whose ages ranged from 20 to 47 (mean 30; SD 8.0) participated in this study. Their mean height was 177.3 cm (SD 6.4) and mean weight was 80.5 kg (SD 12.0).

Apparatus

The Lumbar Motion Monitor (LMM)[23] (Figure 1) was used to monitor the time series of RoM data of the low-back movement. A portable 386 based PC was used to collect and store the data. Later, peak angular velocity and peak angular acceleration were computed by differentiation in customized software developed in the Biodynamics laboratory[13]. A target screen was placed in front of the subject to give a real time visual feedback of sagittal trajectory during the oscillatory bending. Trunk movement data were digitized and stored at 60-Hz sampling rate via an A/D converter. This data acquisition system is depicted in Figure 2.

Table 1. Twenty-three trials including a ballistic condition (1 trial) and 11 ID conditions (22 trials)

Trial #	*RoM (deg)*	*Target (deg)*	*Computed index of difficulty*
1	Preferred	None	n/a
2	15	12	1.32
3	10	8	1.32
4	10	6	1.59
5	15	9	1.59
6	15	7.5	2
7	20	10	2
8	10	4	2.33
9	20	8	2.33
10	15	5	2.59
11	30	10	2.59
12	20	6	2.74
13	30	9	2.74
14	30	7.5	5
15	40	10	3
16	20	4	3.33
17	40	8	3.33
18	30	4.5	3.73
19	40	6	3.73
20	30	4	3.91
21	40	5.3	3.91
22	30	3	4.32
23	40	4	4.32

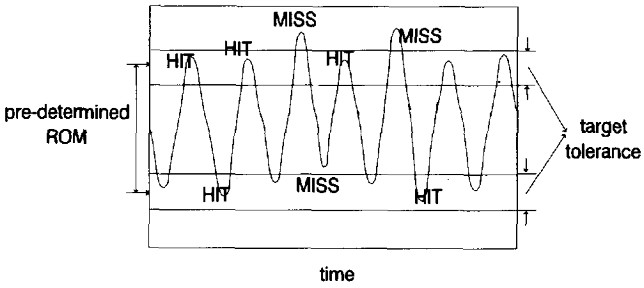

Figure 3. Example of hitting and missing the target on the feedback screen.

Experimental design

Based on the Fitts' paradigm, different indices of difficulty (IDs) were developed and used as independent measures which was consisted of various ranges of motion (A) and target tolerances (W). The range of IDs was determined based on previous studies[18,20,24]. The largest RoM was selected from the maximum RoM reported in previous study[13] and tested on pilot subjects. The smallest target tolerances were selected for pilot subjects not to create visual difficulties. The first trial was designed to measure the performance at subjects' self-selected RoM and maximum comfortable speed. This is a standard protocol that has been used to quantify the trunk dynamic performance without controlled RoM[13,14]. The other 22 trials from 11 ID conditions were designed to measure subjects' both dynamic performance and maximum control capability. The individual experimental conditions of 23 trials are shown in Table 1. Information processing capacity (1/b), based on Fitts' law, was used as a dependent measure. Peak angular velocities, and peak angular accelerations from each flexion/extension cycle were averaged over all cycles and used as dependent measures.

Procedures

After a subject was fitted with the LMM on his back, he was briefly instructed on how to use the screen feedback (Figure 3) in front of him. Then he was told to warm up and practice in order to familiarize himself with the task. For the first trial the subject was asked to flex and extend the trunk continuously as fast as he could for 10 s without specification of any target. From the second trial on, after a brief practice with the screen feedback, the subject was asked to perform controlled oscillatory bendings as accurately and as fast as he could for 10 s. If the subject missed the target more than twice, he was asked to try it again (Figure 3). The subject was verbally encouraged to perform at his best level of effort during the trials. The order of 22 trials with controlled RoM was randomized.

Data analysis

First, the average movement time (MT) per flexion/extension cycle in 11 ID conditions were computed to examine the linear relationship between ID and MT. A regression analysis was performed, and the slope (b) was used to compute the information processing capacity (1/b) of individual subject. Also the peak flexion and extension velocity and acceleration of the complete cycles were computed by customized software, and coefficients of variation (CV: (SD/mean) × 100) of velocity and acceleration were computed to show the variability difference between controlled RoM and self-selected RoM condition.

Second, a smaller set of ID conditions was seleted in order to reduce the length of the protocol for LBP patients. The performance parameters including flexion velocity, extension velocity, flexion acceleration, and extension acceleration were rank-ordered among 20 subjects. Those four rank-ordered scales were added up to produce one performance scale, which is a composite score of different dimensions of velocity and acceleration. Then Spearman correlation analysis was performed to examine the degree of association between ID conditions based on the composite scale. The degree of association (correlation coefficients) allowed us to regroup 11 IDs into a smaller number of groups in which the performance scales were correlated with each other. Next, the mean values of dynamic parameters in each trial were adjusted through analysis of covariance in order to reduce the inherent covariability created by different RoMs in different ID conditions. They were also normalized by the maximum velocity and acceleration. This process made the dynamic parameters completely independent of RoM and non-dimensional. Then we operationally defined a Dynamic Consistency Scale (DCS) which measures the distance between four dynamic parameters of individual peformance. This value identifies which ID condition provides more consistent dynamic information of the trunk than the others. The DCSs were computed according to equation (2).

Table 2. Coefficients of linear regression line from oscillatory flexion and extension of the trunk and information processing capacity based on Fitts' equation

Subject	*Slope (b)*	*Intercept (a)*	R^2	*Inf. pro. capacity (1/b) (bit/s)*
1	0.37	0.08	0.91	2.70
2	0.39	−0.21	0.83	2.56
3	0.33	0.07	0.81	3.03
4	0.22	0.17	0.94	4.55
5	0.31	0.09	0.70	3.23
6	0.25	0.25	0.67	4.0
7	0.17	0.34	0.62	5.88
8	0.27	0.10	0.86	3.70
9	0.28	0.19	0.93	3.57
10	0.19	0.27	0.83	5.26
11	0.32	0.06	0.78	3.13
12	0.36	0.24	0.87	2.78
13	0.22	0.30	0.87	4.55
14	0.36	0.47	0.75	2.78
15	0.20	0.47	0.78	5.0
16	0.19	0.52	0.84	5.26
17	0.21	0.45	0.55	4.76
18	0.17	0.65	0.60	5.88
19	0.29	0.34	0.56	3.45
20	0.17	0.40	0.79	5.88
Mean (SD)	0.26 (0.07)	0.26 (0.20)	0.77 (0.11)	4.23 (1.43)

Table 3. Comparison of dynamic performance parameters between trial 1 without RoM control and trials 2–23 with RoM control

	Self-selected RoM			*Controlled RoM*		
	Mean	*SD*	*CV*	*Mean*	*SD*	*CV*
Flex vel. (deg/s)	141.95	42.71	30.1	68.55	11.57	16.9
Ext vel. (deg/s)	150.37	44.23	29.4	70.15	11.73	16.7
Flex acc. (deg/s^2)	774.26	224.24	30.0	407.68	108.44	26.6
Ext acc. (deg/s^2)	793.48	224.61	28.3	405.22	113.48	28.0

$$\mathrm{DCS} = [(\underline{\mathit{flex.\ vel}}^{*}. - \underline{\mathit{ext.\ vel.}})^2 + (\underline{\mathit{flex.\ vel.}} - \underline{\mathit{flex.\ acc.}})^2 + (\underline{\mathit{flex.\ vel.}} - \underline{\mathit{ext.\ acc.}})^2 + (\underline{\mathit{ext.\ vel.}} - \underline{\mathit{flex.\ acc.}})^2 + (\underline{\mathit{ext.\ vel.}} - \underline{\mathit{ext.acc.}})^2 + (\underline{\mathit{flex.\ acc.}} - \underline{\mathit{ext.\ acc.}})^2]^{1/2} \qquad (2)$$

* $\underline{\mathit{flex.\ vel.}}$: adjusted and normalized flexion velocity

The lowest possible score of DCS is zero, which signifies the absolute consistency between the dynamic performance parameters. Finally, the DCS and correlation coefficients were used to select the fewer number of ID conditions. Moreover, the selection process was validated by testing the difference between the slope and intercept computed for each individual by using all 11 IDs or the seleted three ID conditions. MANOVA was used to perform this validation.

Results

Individual slope and intercept were computed from Fitts' equation and their R^2 values from 11 IDs are summarized in Table 2. In Table 2, R^2 shows how well the linear regression model represents the relationship between ID and MT during the trunk movement. According to the Fitts' equation, the information processing capacity (inverse of the slope b, 1/b) of the 20 subjects was computed as 4.23 (SD 1.43 bits/s. Table 3 shows the reduction of variability in velocity when RoM is controlled. The coefficient of variation (CV) [(SD/mean) × 100] of angular velocity of trunk movement with controlled RoM was reduced by 56% compared to the condition with self-selected RoM. The CV of acceleration was unaffected by controlling the RoM.

In Table 4, Spearman correlation coefficients among 11 IDs are summarized. The dynamic consistency scale (DCS) values are computed and summarized in Table 5. In Table 5, ID conditions were regrouped based on correlation coefficients and DCS value. The DCS under the self-selected RoM condition was shown to be greater than those DCSs under the controlled RoM condition.

Based on results, the fewer number of ID conditions were selected according to the following steps: First, ID conditions with relatively smaller DCS (less than .40) were selected such as, group 1: ID 1.59, 2.33, 2.59; group 2: ID 2.74, 3.00; group 3: ID 3.33; group 4: ID 3.73. Second, the ID 3.73 of group 4 was dropped to

Table 4. Spearman correlation coefficients between dynamic performance scales from different ID conditions. The first column from the right side shows the correlation coefficient between information processing capacity and dynamic performance scale

	Dynamic performance scale in each ID condition											*Self-select RoM*	*Inf. pro. capacity*
	ID 1.32	*ID 1.59*	*ID 2.00*	*ID 2.33*	*ID 2.59*	*ID 2.74*	*ID 3.00*	*ID 3.33*	*ID 3.73*	*ID 3.91*	*ID 4.32*		
1.32	1.00	0.78	0.84	0.82	0.68	0.53	0.11	0.03	–0.09	0.04	0.01	0.57	0.25
1.59	–	1.00	0.80	0.89	0.78	0.66	0.30	0.36	0.16	0.29	0.14	0.29	0.44
2.00	–	–	1.00	0.90	0.79	0.78	0.37	0.30	–0.02	0.15	0.03	0.47	0.15
2.33	–	–	–	1.00	0.80	0.75	0.44	0.33	0.14	0.27	0.15	0.39	0.31
2.59	–	–	–	–	1.00	0.75	0.54	0.40	0.17	0.34	0.16	0.61	0.22
2.74	–	–	–	–	–	1.00	0.76	0.46	0.40	0.44	0.41	0.45	0.08
3.00	–	–	–	–	–	–	1.00	0.55	0.54	0.55	0.49	0.33	–0.14
3.33	–	–	–	–	–	–	–	1.00	0.54	0.42	0.30	–0.10	0.13
3.73	–	–	–	–	–	–	–	–	1.00	0.70	0.81	0.06	0.35
3.91	–	–	–	–	–	–	–	–	–	1.00	0.73	0.15	0.45
4.32	–	–	–	–	–	–	–	–	–	–	1.00	0.15	0.40
No ID	–	–	–	–	–	–	–	–	–	–	–	1.00	–0.01

$P<0.001$ if $r>0.74$, $P<0.001$ if $r>0.55$.

avoid too small a target size to read (2.25 deg when RoM is 15 deg). Finally, from the remaining three groups, six combinations of three ID conditions were selected. The results of MANOVA for the slope and intercept of each combination of three IDs and 11 IDs are shown in Table 6.

Slope and intercept from all six combinations of three IDs were found to be no different from those in 11 ID conditions even at alpha = 0.1 level ($P>0.12$). This result gave the experimenter freedom to choose any of three ID conditions from Table 6. The following guidelines were used to choose the final protocol. (1) Three IDs whose R^2 value were greater than 0.7; (2) three IDs, preferably not adjacent each other, which would cover a greater RoM of the subject. Accordingly, ID 1.59, ID 2.74, and ID 3.33 were selected. Figure 4 illustrates the results for subject 1. The regression lines are fitted to the data based on three ID and 11 ID conditions.

Table 5. Dynamic consistency scale (DCS) of dynamic performance. New groups of ID are shown with superscript in the first column based on the correlation coefficients

ID	*Trial*	*DCS Mean (SD)*	*RoM (deg)*	*Target (deg)*
n/a	1	0.68 (0.44)	Self-selected	None
1.32^1	2,3	0.42 (0.22)	10 & 15	8 & 12
1.59^1	4,5	0.32 (0.13)	10 & 15	6 & 9
2.00^1	6,7	0.44 (0.22)	15 & 20	7.5 & 10
2.33^1	8,9	0.30 (0.16)	10 & 20	4 & 8
2.59^1	10,11	0.29 (0.17)	15 & 30	5 & 10
2.74^2	12,13	0.35 (0.14)	20 & 30	6 & 9
3.00^2	14,15	0.31 (0.13)	30 & 40	7.5 & 10
3.33^3	16,17	0.27 (0.11)	20 & 40	4 & 8
3.73^4	18,19	0.33 (0.14)	30 & 40	4.5 & 6
3.91^4	20,21	0.40 (0.15)	30 & 40	4 & 5.3
4.32^4	22,23	0.44 (0.16)	30 & 40	3 & 4

1,2,3,4: groups correlated with each other.

One limitation in using the protocol was that some LBP patients would not be expected to bend more than 20 deg[13]. So additional steps were taken to see whether or not a smaller RoM and target tolerance could be used. ANOVA was conducted to examine the information processing capacity between different RoMs and targets within the same ID, and found no significant effect of RoM and target ($P>0.09$). Based on this result it was suggested that clinician may adjust the RoM and target tolerance if it is necessary to accommodate low-back patients with physical limitations. In this way the performance of subjects can be measured without exceeding the subjects physical capability. Adjusted RoM (A) and target tolerance (W) based on the selected ID conditions are tabulated in Table 7.

Discussion

First of all a linear relationship between ID and MT (Figure 3) was found in this study. This means that Fitts' experimental paradigm is still a proper tool to investigate the information processing capacity of the trunk motion. Second, in Table 3, it was shown that the predetermined RoM greatly reduced the group variability of the velocity during flexion and extension of the trunk. This reduction of group variance of the velocity can improve the separability between normal subjects and LBP patients. However, the mean velocity difference between the normal subjects and patients

Table 6. The slope, intercept, and R^2 of regression equation from three ID conditions (first three columns). MANOVA test results showing insignificant differences between three IDs and 11 IDs (fourth column)

Groups of 3-ID conditions	*Slope Mean (SD)*	*Intercept Mean (SD)*	R^2	*Wilks' Lambda (Pr> F) 3 IDs vs 11 IDs*
1.59, 2.74, 3.33*	0.22 (0.07)	0.37 (0.24)	0.70 (0.17)	0.2234
1.59, 3.00, 3.33	0.24 (0.07)	0.36 (0.23)	0.71 (0.20)	0.3855
2.33, 2.74, 3.33	0.30 (0.10)	0.12 (0.29)	0.62 (0.20)	0.2324
2.33, 3.00, 3.33	0.31 (0.09)	0.10 0.27)	0.58 (0.21)	0.1173
2.59, 2.74, 3.33	0.28 (0.11)	0.24 (0.38)	0.43 (0.29)	0.7946
2.59, 3.00, 3.33	0.31 (0.12)	0.13 (0.38)	0.42 (0.27)	0.3959
11 IDs	0.26 (0.07)	0.26 (0.20)	0.78 (0.11)	n/a

*Selected as the final three ID conditions.

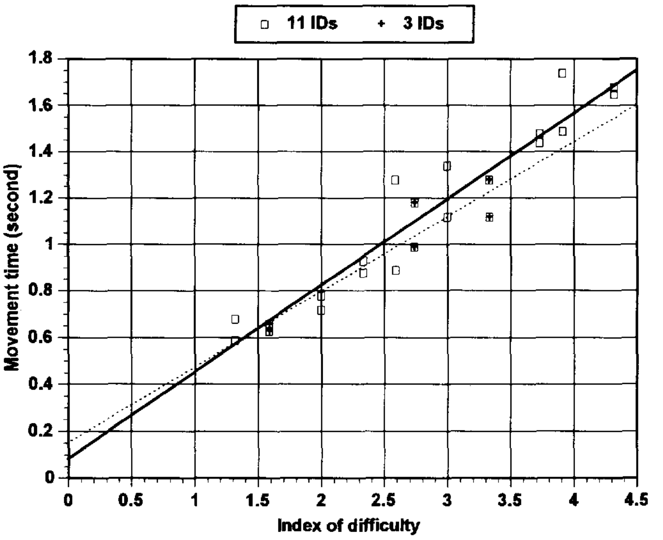

Figure 4. An example of individual control capability (subject 1) shown as a scatter plot and linear regression line. + from three IDs (1.59, 2.74, 3.33; six trials). R^2 = 0.89, slope = 0.32, intercept = 0.16, dashed line; from 11 IDs (22 trials). R^2 = 0.91, slope = 0.37, intercept = 0.08, solid line.

may be also reduced due to the predetermined amplitude of movement. Thus this separability issue will be investigated further in the future study. Third, in Table 2, the information processing capacity of the trunk was computed in terms of bits/s (mean, 4.23; SD, 1.43 bits/s), and this control parameter showed the low correlation (0.08 to 0.45 in Table 4) with the dynamic performance scale derived from the velocity and acceleration. This made us speculate that this motor control parameter is independent of subject's ability to generate the dynamic trunk motion. Thus this parameter, information processing capacity, can be treated as a new quantifier of the trunk motor performance. Indeed the neurophysiological determinant of the dynamic trunk function has been elusive so far; thus this information processing capacity could be used as a coordination index of dynamic trunk performance among healthy subjects and LBP patients. To understand this new motor control parameter of the trunk further, the effect of gender, age, and type of low back disorder will be investigated in the future.

For the final selection of the protocol for both healthy and LBP patients, it was necessary to consider the physical limitations among LBP patients in terms of standing endurance and RoM. Thus the protocol was shortened by choosing the several ID conditions, and the RoMs in the protocol were adjusted to accommodate the physical limitation of LBP patients. The series of statistical analyses, including correlation analysis among the ID conditions and Dynamic Consistency Scale (DCS), were used to assist in finding the optimal set of condition. Moreover the validity of the shortened protocol was examined by comparing the slope and intercept of regression equations derived from three ID conditions to those from 11 ID conditions. The final protocol will take approximately 15 min compared to an hour with the original protocol.

Clinically this motor control parameter may reveal the capability of neuromuscular system of the trunk among both normal subjects and LBP patients. For example, if the subject shows the increase of the slope which is equivalent to the decrease of information processing capacity, it may be speculated that he or she takes more time to process the additional information to control the difficult task. It can be also speculated that the increased information processing of patients might be due to the complex motor programmes needed to coactivate the muscle to avoid further loading of painful structure. These issues can be further investigated by using biomechanical models utilizing kinematics, kinetics, and neuromuscular excitation information (i.e. EMG driven models[25,26]).

Conclusion

This protocol provided a new quantitative method assessing the control capability/coordination of the trunk muscle during dynamic motor performance. Since the quantification of coordination of trunk muscle has been an important issue in sport and rehabilitation, this finding may add a new way of quantifying control capability of the trunk. In the future, this new protocol will be tested among LBP patients and control group to examine the hypotheses raised in this study.

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Table 7. Adjusted movement amplitude (A) and target tolerance (W) for different maximum RoM

	Max. RoM									
	20–25 deg		*25–30 deg*		*30–35 deg*		*35–40 deg*		*40 and above*	
ID	A	W	A	W	A	W	A	W	A	W
1.59	10 & 15	6 & 9	10 & 15	6 & 9	10 & 15	6 & 9	10 & 15	6 & 9	10 & 15	6 & 9
2.74	15 & 20	4.5 & 6	15 & 20	4.5 & 6	20 & 25	6 & 7.5	20 & 25	6 & 7.5	20 & 30	6 & 9
3.33	15 & 20	3 & 4	20 & 25	4 & 5	25 & 30	5 & 6	30 & 35	6 & 7	35 & 40	7 & 8

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Appendix

Fitts' Law as described in equation 1 related the movement time to the index of difficulty. For the same movement amplitude, a smaller target width causes the increase in the index of difficulty which leads to larger movement time. The concept of how information is represented in terms of bits is based on theory of communications[19]. The number of bits refer to the number of the possible outcomes or events. During the movement if the width of the target is W and the amplitude of movement is A, the smallest range of angular position in this context is the $W/2$, since we have not distinguished between overshooting or undershooting of the target. The event or outcome of interest is the number of possible final position of the trunk, we need to compute the ratio: $A/(0.5 * W) = 2A/W$. The number of bits needed to represent this ratio is the index of difficulty (ID): $\mathrm{ID} = \log_2 (2A/W)$.

Fitts[19] has shown that the movement time remains relatively invariant with respect to A or W if the ID is the kept the same, suggesting that the information processing capacity ($1/b$) is constant.